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Scenario comparisons of gasification technology using energy life cycle assessment for bioenergy recovery from rice straw in Taiwan

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ABSTRACT

This study uses different scenarios to evaluate, by means of energy life-cycle assessments (ELCAs), the energy balance of potential gasification technology and limitation boundaries in Taiwan. Rice straw is chosen as the target material in this study because it is the most significant agriculture waste in Taiwan. Energy products include syngas ($CO + H_2$), methane, carbon dioxide and carbon black residue. The scenarios simulate capacities of 50,000–200,000 tons/year. The distances of collection and transportation are calculated by a circular area 50–100 km in diameter. Also, the on-site and off-site pretreatments of rice straw are evaluated. For this optimum scenario case, the average of the total input energy for the assessed systems is about 15.9% of the average output energy; the value of the net energy balance (NEB) is 0.841. Every technological process has positive energy benefits at all on-site scenario cases. As the capacity is increased, the energy consumption required for transportation increases and the values of the energy indicators decrease. According to the limitation boundaries from the tendency model at on-site cases, the suggested transportation distance and treatment capacity are below 114.72 km and 251,533 tons/year, respectively, while the energy return on investment (EROI) value is greater than 1.

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1. Introduction

With the continuous rise and fluctuations in fossil fuel prices, along with increasing environmental concerns regarding emissions produced through fossil fuel utilization, biomass is seen as a promising renewable energy source that would meet a variety of energy needs and could ultimately replace fossil fuels. Biomass is the fourth largest source of energy in the world, contributing about 35% of primary energy consumption in developing countries and 3% in industrialized countries [1]. The energy and greenhouse gas (GHG) balances of bioenergy systems differ depending on the sources of feedstock, conversion technologies, end-use technologies, system boundaries and the reference energy system with which the bioenergy chain is compared. Regional differences can be also significant, especially with respect to land use, biomass production patterns and the reference energy system, and the life cycle assessment (LCA) results can change as technologies evolve [2]. LCA represents a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, as well as the associated environmental impacts directly attributable to a product or service throughout its life cycle. Adoption of environmentally-friendly waste-to-energy (WTE) technologies is one effective way which could also help reduce GHG emitted into the atmosphere [3].

Energy life cycle assessment (ELCA) is a methodology used to determine both the environmental and energy performance, but results can differ for apparently similar bioenergy systems. Differences are caused by a number of reasons, including type and management of raw materials, conversion technologies, end-use technologies, system boundaries and the reference energy system with which the bioenergy chain is compared [4–6]. At one time this methodology was mainly dedicated to industrial products. Although the ISO 14040-series provides the standard for LCA, it was applied in a variety of ways which often led to diverging results, especially in the case of biofuels. LCA of biofuels is often limited to energy and/or GHG balance. Several LCA studies have been completed with various frameworks, scopes, accuracy, transparency and consistency levels, depending on the stated goal, which may be process design-, operation- or policy-oriented [7]; all of these works make it easy to minimize the differences of the results on a rational basis, even when addressing the same biofuel pathway.

A wide range of biomass sources can be used to produce bioenergy in a variety of forms. For instance, process residues and energy crops can be utilized to generate electricity, heat, combined heat

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Nomenclature

Abbreviations

ELCA	energy life-cycle assessment
NEB	net energy balance
GHG	greenhouse gas
LCA	life cycle assessment
WTE	waste-to-energy
BTL	biomass to liquid
GTL	gas to liquid
LCIA	life cycle inventory analysis
PC	portable crusher
RFPS	radio-frequency plasma systems
MWS	microwave-induced systems
DGS	downdraft gasifier systems
PTS	plasma torch systems
CT	cooling tower
EP	electrostatic precipitator
WS	wet scrubber
NEA	net energy analysis
EBA	energy balance analysis
NER	net energy production ratio
EROI	energy return on investment
NEB	net energy balance
TER	total energy ratio
Er	energy ratio
RDF	refused-derived fuel
LCAMWS	gasification facility using MWS in LCA
LCAPTS	gasification facility using PTS in LCA
IGCC	integrated gasification combined cycle
APEs	air pollution control equipments
LCARFPS	gasification facility using RFPS in LCA
LCADGS	gasification facility using DGS in LCA

Symbols

η_E	overall thermal efficiency (%)
E_P	sum of energy contents of products (MJ)
E_X	sum of energy values of external energy inputs except feedstock (non-renewable) (MJ)
E_{XEAS}	non-renewable, with every assessed step in the life-cycle process of external energy input values considered, except feedstock (MJ)
E_F	energy of feedstock (rice straw) (MJ)

and power and gas/solid/liquid biofuels. In fact, utilization of modern bioenergy applications is growing, especially the co-firing of biomass with coal, gasification technologies, transportation biofuel generation (mainly bioethanol and biodiesel) and biomass to liquid (BTL) and gas to liquid (GTL) technologies [8,9]. Unlike dedicated bioenergy crops, biowastes and residues are not produced specifically for use as an energy resource, but are the result of economic activity and the production of goods in almost all sectors of the economy. A fundamental role is played by biomass supply, because the source of the biomass significantly impacts LCA outcomes [2].

Crop residue, such as rice straw, produced in abundance on Taiwan, can provide a sustainable biomass resource in the making of biocoal for producing bioelectricity, thus enhancing Taiwan's energy security. Rice is the main grain crop in Taiwan. The annual average production of paddy rice was about 1.6 million tons from 2001 to 2005 [8]. Rice straws are the non-edible plant parts left in the field after the harvesting of paddy rice. According to Shie et al. [8], the production of rice straw amounts to about 2.2 million tons annually. This considerable amount of rice straw requires appropriate disposal in order to avoid local pollution problems as the result of open burning, which is harmful to the air quality and environment from increased CO_2 emissions [10].

In this study, we analyzed different scenario capacities of 50,000–200,000 tons/year for collection areas 50–100 km in diameter using the ELCA method. Energy outputs from different technologies and collection scenarios have been compared and the desirability of the energy indicators addressed and evaluated. The objective of this article is to propose suitable boundary conditions for biomass utilization in Taiwan.

2. Methodology

2.1. Raw materials

The planting area of rice in I-Lan, Taiwan was 9375 ha in 2007, with 5.63×10^5 tons of wet and fresh rice straw remaining at the farms following the rice harvest (6 tons/ha) [6]. The total amount of rice straw in north Taiwan was about 2.33×10^5 tons, as listed in Table 1. The block density of drying rice straw is 990 kg/m^3. The characteristics of the original rice straw as used in this study are as described in a previous study [8]. The results of the proximate analysis are 85.78, 4.55 and 9.67 wt% of combustible value, moisture and ash, respectively. The heating value is 4042 kcal kg^{-1}, and the contents of the C, N, H and S of rice straw are 41.41, 0.95, 5.19 and 0.2 wt%, respectively [8].

2.2. Life-cycle processing and scenario conditions

2.2.1. Life-cycle processing

LCA is a systematic process for identifying, quantifying and assessing environmental impacts throughout the life cycle of a product, process or activity. It is used to consider energy and material use and products released into the environment from 'cradle to grave' (i.e., from raw material extraction through manufacturing, transportation, use and disposal). In the life-cycle inventory analysis (LCIA) phase, data are collected to quantify inputs and outputs of the system being studied in order to meet the specific goals of the defined study. The types of data include energy, raw materials and other physical inputs; products, co-products and wastes; releases to air, water and soil; and other environmental aspects. Input and output data are collected for all the processes in the system, especially in the energy balance phases.

Table 1
Harvested land areas of rice corps and yields of rice straw in north Taiwan counties.

	Planted area (ha)	Amount of rice straw[a] (tonne)
I-Lan County	9375	5.63×10^4
New Taipei City	235	1.14×10^3
Taoyuan County	10,784	6.47×10^4
Hsinchu County	6694	4.02×10^4
Miaoli County	11,774	7.06×10^4
Total	38,862	2.33×10^5

[a] Wet and fresh rice straw (amount of rice straw = planted area (ha) × 6 (tonne/ha)).

Table 2
Scenario conditions of the biomass energy plant using rice straw as feedstock for the ELCA.

Biomass raw material	Location	Capacity (tonne/year)	Transportation distance (km)	RDF preparation	Scenario case name
Rice straw	I-Lan, Taiwan	50,000	50	Off-site	A
	I-Lan, Taiwan	65,000	50	Off-site	B
	I-Lan, Taiwan	80,000	60	Off-site	C
	North of Taiwan	100,000	70	Off-site	D
	North of Taiwan	150,000	80	Off-site	E
	North of Taiwan	180,000	90	Off-site	F
	North of Taiwan	200,000	100	Off-site	G
	I-Lan, Taiwan	50,000	50	On-site	H
	I-Lan, Taiwan	65,000	50	On-site	I
	North of Taiwan	200,000	100	On-site	J

In the present evaluation, the pre-treatment process for the ELCA of rice straw was the same as that of a previous study [6] and also divided into on-site and off-site conditions. In the on-site situation, three pieces of pre-treatment equipments simulated in series were used: a dryer, portable crusher (PC) and pelletizer, each operated near the rice farm with electricity supplied by generators. Four alternative energy production processes, radio-frequency plasma systems (RFPS), microwave-induced systems (MWS), downdraft gasifier systems (DGS) and plasma torch systems (PTS), were assessed. The condensation and air pollution control devices included a cooling tower (CT), electrostatic precipitator (EP) and wet scrubber (WS). Detailed descriptions of these production systems can be found in the reference literatures [6,8,10–16]. The scenario condition for the biomass energy plant of the plant capacity for treating dry rice straw was assumed to be 50,000–200,000 tons/year^{-1}. Operating hours are generally assumed to be 8000 h/year^{-1} [17]. With respect to the plant capacities, transportation distances were within a circular area 50–100 km in diameter, including all the area north of Taiwan. The different scenario conditions are listed in Table 2; a 20-ton diesel truck was used.

2.3. Energy analysis indicators

Several energy indicators, including net energy analysis (NEA), energy balance analysis (EBA), net energy production ratio (NER) and energy return on investment (EROI), were used in this study. Detailed definitions of these indicators are cited in our previous study [6]. The EROI ratio of the energy delivered takes into consideration the energy used directly and indirectly in the process. EROI is defined as:

$$\mathrm{EROI} = E_P/E_X \quad (1)$$

where E_P is the sum of energy contents of products (gaseous and solid products) and E_X is the sum of energy values of external energy inputs except feedstock (non-renewable).

NER indicates how much energy is produced as salable products in relation to the external, non-feed and energy inputs. NER is derived as:

$$\mathrm{NER} = (E_P - E_X)/E_X \quad (2)$$

The overall thermal efficiency (η_E) for the production of useful energy products is defined as:

$$\eta_E = 100 \times (E_P/(E_F + E_X)) \quad (3)$$

where E_F is the energy of feedstock (rice straw used in this study).

The net energy balance (NEB) and total energy ratio (TER) are defined as:

$$\mathrm{NEB} = (E_P - E_X)/E_p \quad (4)$$

$$\mathrm{TER} = E_X/E_p \quad (5)$$

The energy ratio (Er) is the ratio of the input energy of every assessed step in the life-cycle process to total output energy, and is defined as:

$$\mathrm{Er} = E_{XEAS}/E_p \quad (6)$$

where E_{XEAS} is non-renewable, with every assessed step in the life-cycle process of external energy input values considered, except feedstock.

Table 3
Material and building energy requirements for constructing production facilities in the life-cycle process of rice straw for bio-energy.

	Material mass (tonne)	Input energy (MJ/year)	Input energy (MJ/tonne-year)
Concrete (2 MJ/kg)[a]	1.96×10^4	1.96×10^6	9.80
Structural carbon steel (25 MJ/kg)[a]	1.0×10^3	1.25×10^6	6.25
Building siding carbon steel (25 MJ/kg)[a]	3.0×10^2	3.75×10^5	1.88
Stainless steel gases storage tanks (26.5 MJ/kg)[a]	2.87×10^3	1.09×10^5	0.54
Stainless steel piping (26.5 MJ/kg)[a]	91	1.21×10^5	0.60
Other stainless steel equipment (26.5 MJ/kg)[a]			
Dryer	50	1.33×10^5	0.66
PC	17.67	4.68×10^4	0.23
Pelletizer	4.8	1.27×10^4	0.06
RFPS	4	2.76×10^4	0.14
MWS	4	6.89×10^3	0.03
DGS	10	3.45×10^4	0.17
PTS	5	1.15×10^4	0.06
APE[b]	10.5	1.81×10^4	0.09

[a] Number in parentheses is the energy requirement per kilogram of material [16].

[b] Air pollution control equipments (APEs), including cooling tower (CT), cyclone, electrostatic precipitator (EP) and wet scrubber (WS).

Table 4
Energy of household labor using in the production facilities in the life-cycle process of rice straw for bio-energy.

Types of production facilities	Labor per day[a]	Labor household members per day[f]	Energy requirement per day (MJ/day)[g]	Energy requirement per year[h] (MJ/year)
RFPS	54[b]	86	0.90	310.95
MWS	15[c]	24	0.25	86.78
DGS	30[d]	48	0.50	173.55
PTS	15[e]	24	0.25	86.78

[a] Every labor works 8 h per day and three people for 24 h (one day).
[b] RFPS needs 54 laborers (=18 laborers × 24 h/8 h).
[c] MWS needs 15 laborers (=5 laborers × 24 h/8 h).
[d] DGS needs 30 laborers (=10 laborers × 24 h/8 h).
[e] PTS needs 15 laborers (=5 laborers × 24 h/8 h).
[f] Supervision and maintenance household is 59% of the sum of operating labor and labor household members per day is labor per day × 1.59.
[g] One 35-year-old people needs 2500 calories (10.45 kJ) per day according to the information of "Dietary Reference Intakes" (http://food.doh.gov.tw/DRIS/DRIs.php).
[h] one plant works 334 days per year.

Table 5
Energy requirements for production facilities in the life-cycle process of rice straw for bio-energy.

Life-cycle processing	Types of equipments	Power (kW)	Energy requirement per tonne (MJ/tonne)	Energy requirement per year[a] (TJ/year)
Pre-treatment	Dryer	300	108	21.6
	PC	126	18.14	3.63
	Pelletizer	110	118.8	23.76
		Sub-total	244.94	48.99
Production	RFPS	275.94	39.74	7.95
	MWS	92.18	13.27	2.65
	DGS	165.81	23.87	4.78
	PTS	298.76	43.02	8.60
Condensation	CT	125.53	18.08	3.62
Air pollution control, APC	EP	251.07	36.15	7.23
	WS	125.53	18.08	3.62
		Sub-total	54.23	10.85

[a] Treatment capacity = 80,000 tonne/year.

Table 6
Energy of gaseous products derived from production facilities in the life-cycle process of rice straw for bio-energy.

Types of production facilities	Gaseous products	Yield per year (tonne/year)	Heating value (kJ/mol)	Energy production per tonne (MJ/tonne)	Energy production per year[a] (TJ/year)
LCARFPS[c]	CO	1.22×10^5	282.99	6.14×10^3	1229
	H_2	8.32×10^3	285.84	5.94×10^3	1188
	CH_4	1.71×10^3	890.95	4.75×10^2	95.12
			Sub-total	1.26×10^4 (1.00×10^4)[b]	2512 (2010)[b]
LCAMWS[d]	CO	2.36×10^4	282.99	1.19×10^3	239
	H_2	7.20×10^3	285.84	5.15×10^3	1029
	CH_4	1.00×10^4	890.95	2.78×10^2	556
			Sub-total	9.12×10^3 (7.30×10^3)[b]	1824 (1459)[b]
LCADGS[e]	CO	–			
	H_2	–	Sub-total	1.10×10^4 (8.80×10^3)[b]	2201 (1761)[b]
	CH_4	–			
LCAPTS[f]	CO	1.74×10^5	282.99	8.79×10^3	1759
	H_2	1.40×10^4	285.84	1.00×10^4	2001
	CH_4	4.00×10^3	890.95	1.11×10^3	223
			Sub-total	1.99×10^4 (1.59×10^4)[b]	3982 (3186)[b]

[a] Treatment capacity = 80,000 tonne/year.
[b] Energy conversion efficiency = 0.8.
[c] Gasification facility using RFPS in LCA.
[d] Gasification facility using MWS in LCA.
[e] Gasification facility using DGS in LCA.
[f] Gasification facility using PTS in LCA.

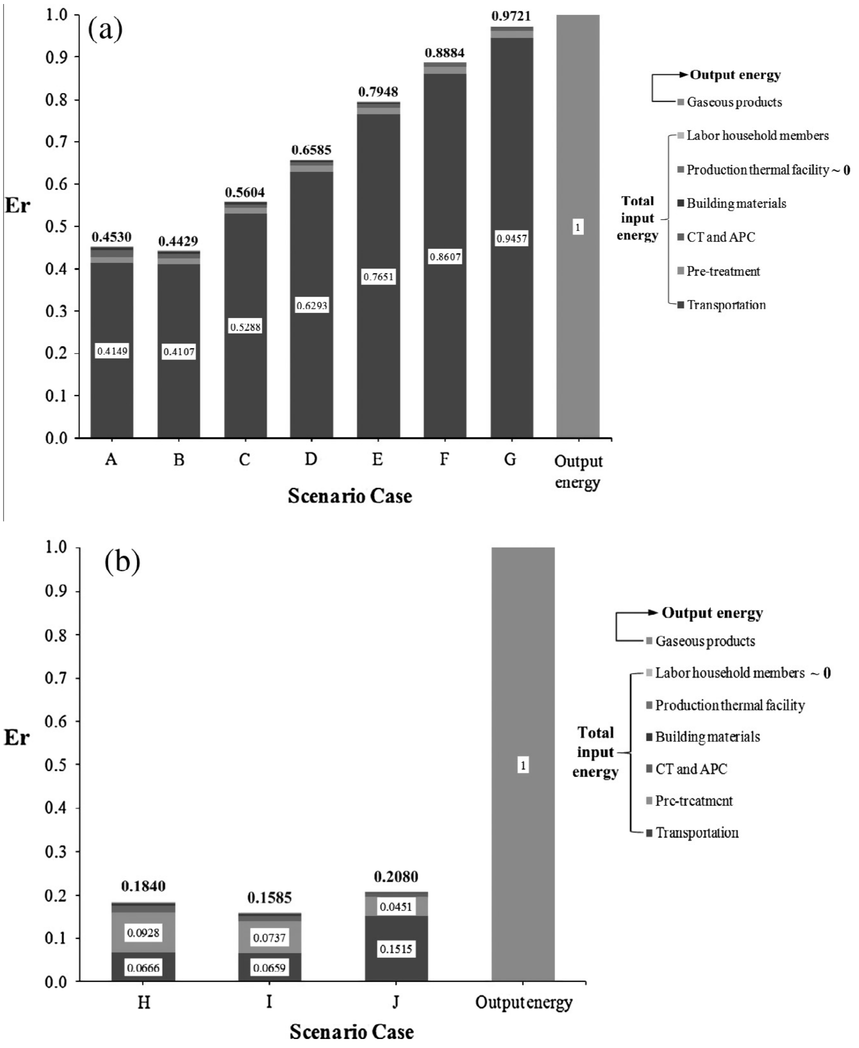

Fig. 1. Er value of the bioenergy production from rice straw in the ELCA. Energy output is expressed as unit energy of the bio-energy. (a) Off-site and (b) on-site.

3. Results and discussion

3.1. Energy use in converting biomass to biofuels

The first phase or step of LCA is the goal and scope definition. The scope of the system also has to define the function of the system. Generally, a flow model (or flow chart), consistent with the system boundaries as specified in the goal and scope and definitions, is constructed. The flow model shows the activities in the system and the input and output flows throughout its life cycle. In this study, LCA involved three main sections: pre-treatment of biomass, syngas production and use of the syngas produced. The energy uses in the LCA process of converting rice straw to biofuels have all been estimated. The building materials, operating bio-fuel production facilities and the workers necessary to sustain the production facility, as well as their households, were also considered, along with the production facilities for all direct and indirect energy inputs [6]. All input data for each stage of the processes were collected from the literature, field study, experimental data or any archival results from assessments. Input and output data were collected for all the processes in the system. Calculations were then performed to estimate the total resources used and the pollution emissions in relation to the functional unit. The result was an inventory of the environmental input and output data of the system under study.

Energy required for the transportation of rice straw with RDF off-site and on-site, as well as the generator fuels used for refused-derived fuel (RDF) on-site, were evaluated according to the diesel fuel used in vehicles. The material and building energy requirements for constructing production facilities in the LCA involved the energy necessary to the production of concrete, carbon steel and stainless steel [18]. Taking the scenario of case G (Table 2) for example, Table 3 shows the material and building energy requirements for constructing production facilities in the LCA. The energy consumption involved in producing the concrete, carbon steel and stainless steel was assumed to be 2, 25, 26.5 MJ/kg, respectively [18]. The maximum input energy was 9.80 MJ/tonne-year of concrete because of the large use of concrete mass in the consideration of 20 year depreciation. Table 4 shows the energy requirements of the labor force. The maximum energy requirement per year was 310.95 MJ/year from RFPS due to its maximum of 63 laborers. Table 5 lists the energy requirements for the production facilities in the LCA. The most energy was used in the pre-treatment process, as shown in Table 5, with an energy requirement per year of 48.99 TJ. In order to feed rice straw into the thermal reactor, crushing and briquetting are needed in the production of RDF. As shown in Tables 3 and 5, it was evident that the energy consumption of the dryers used for torrefaction purposes in pre-treatment was far higher than that of the other processes. In general, the main goal of drying is to decrease the moisture content of solid materials below a certain limit. Drying technology is also part of other industrial processes, for example, the food, chemical, and paper and pulp industries. The main objectives of drying or torrefaction for biomass waste are extended their storage life, quality enhancement, ease of handling and further processing of other products [19].

3.2. Energy yield from gaseous products

The product gas (syngas) is a mixture of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and other hydrocarbons. The raw product gas usually contains some solid particles, such as unreacted charcoals, ash and bed materials, which need to be separated. Therefore, the crude syngas was immediately put into a cyclone and electrostatic precipitator in order to eliminate these particles. The syngas was further passed through a wet scrubber for gas scrubbing to remove acid gases, such as CO_2, SO_2 and H_2S. The output production of biofuel includes the biofuel itself, as well as any simultaneously generated co-products. For the purposes of energy accounting, we assigned the biofuel itself an energy content equal to its available energy upon combustion. Co-products, such as active carbon, carbon black or residue, are typically not combusted directly; as they can be recovered as solid wastes, we did not assign them an energy content rating. Table 6 lists the energy in the form of gaseous products from the facilities in the LCA. The energy evaluated in the ELCA, in the form of gaseous products from the facilities, had an energy efficiency factor of 0.8 [6]. In the production of electricity, energy efficiency depends on the generating engine, which can be designed and assessed using the different power processes described in the next steps [20]. The total energy requirement (input) and production (output) of the four assessed energy production facilities in the LCA for all scenario conditions were detailed in our previous study [6]. The average of the total input energy at the scenario conditions of off-site and on-site pretreatments with capacities from 50,000 to 200,000 tons/year was in the range of about 0.44–0.97 and 0.16–0.21 of the average output energy (total Er) (Fig. 1), respectively; the values of the NEB were 0.56–0.03 and 0.84–0.79, respectively. Despite our use of expansive system boundaries for energy inputs, the analyses of this study showed that the production of biofuel from rice straw had positive NEBs in all scenario conditions. The optimum scenario was case I (50 km diameter transportation, 65,000 ton capacity and on-site pretreatment). For this optimum scenario, the average of the total input energy for the four assessed energy production systems was about 15.8% of the average output energy; the value of NEB was 0.842. It was obvious that the energy requirements of the transportation and pre-treatment stages constituted the major sources of energy consumption in the LCA. Using solar energy in the natural drying process prior to on-site briquetting for RDF would provide an alternative choice for the energy recovery of rice straw, which would, in turn, assist in reducing transportation energy requirements.

3.3. Comparison of energy indicators

Energy indicators of ELCA, including EROI, NER and η_E, were evaluated according to these output and input energies. EROI is

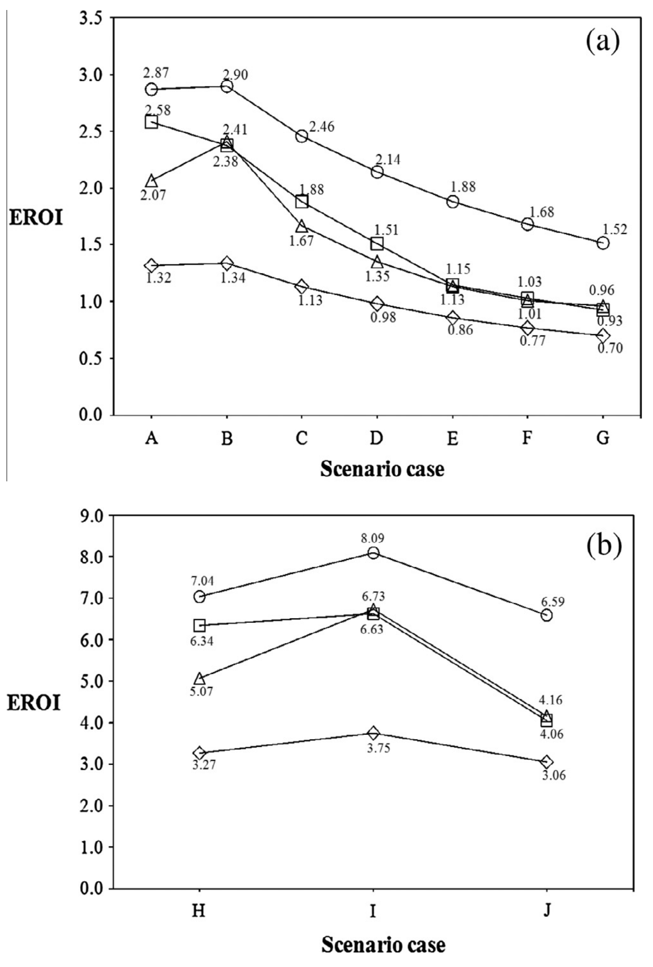

Fig. 2. EROI value of the bioenergy production from rice straw in the ELCA. (a) Off-site and (b) on-site. ○: LCAPTS. □: LCADGS. △: LCARFPS. ◇: LCAMWS.

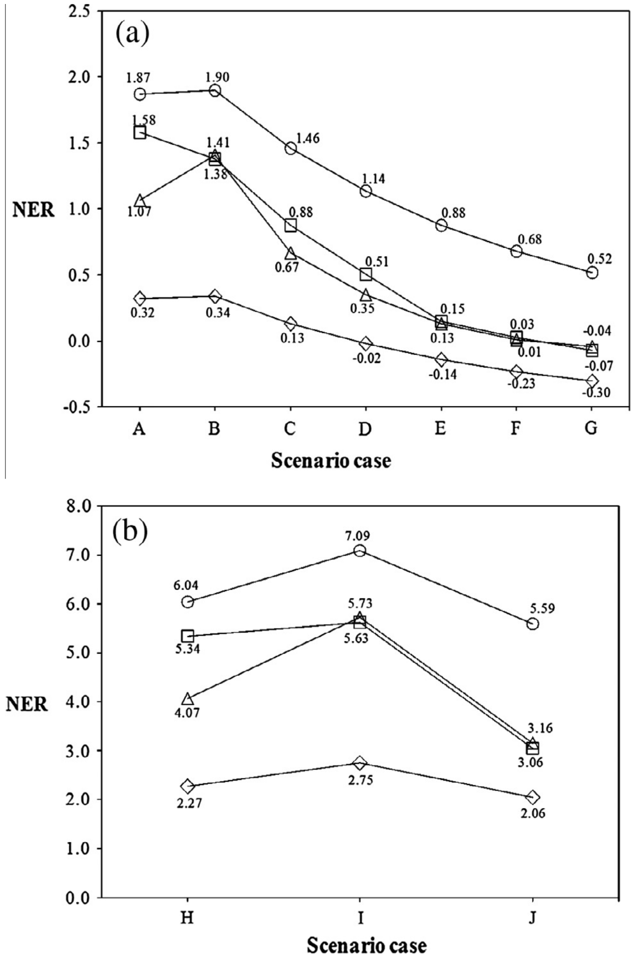

Fig. 3. NER value of the bioenergy production from rice straw in the ELCA. (a) Off-site and (b) on-site. ○: LCAPTS. □: LCADGS. △: LCARFPS. ◇: LCAMWS.

here defined by the ratio of gaining useful energy. Every energy input is taken into the process and converted to produce energy in one or more forms. The value of η_E indicates how much useful energy is produced over and above the energy consumed by the system; this value is considered to be the energy content of the biomass feedstock. When considering losses due to inefficiency, such as friction and heat loss, thermal efficiency values are typically much less than 100%. The ratio of NER indicates how much useful energy is produced over and above the energy consumed by the system if the external, non-biomass energy consumed is replaced, and assuming that the biomass feedstock energy content is zero. Figs. 2–4 show the energy indicators of EROI, NER and η_E, respectively, for the four assessed energy production systems. Except for the system of LCAMWS at off-site, all EROI values of the four assessed systems were larger than 1. Scenario I of LCAPTS had the highest EROI value of 8.09. The NER values of the four assessed energy production systems at on-site were all greater than 1. Also, Scenario I of LCAPTS had the highest NER value of 7.09. The same situation appeared in the value of η_E of 83.36% in Scenario I of LCAPTS. Compared with the other systems, Scenario I of LCAPTS was the optimum scenario case in this study. For on-site pretreatment, the energy indicators increased dramatically because the energy consumption for transportation showed a large decrease. At off-site cases, EROI, NER and η_E all decreased with the increase of transportation distance and treatment capacity. The higher the EROI, the more renewable the biofuel [21]! An NER value greater than zero indicated that an amount of energy equivalent to the sum of the external, non-biomass energy inputs and an additional energy accession of useful fuels was produced: the larger the ratio, the larger the accession.

3.4. Tendency simulation models from energy indicators

Fig. 5 shows the tendency simulation models of EROI, NER and η_E values of LCAPTS for the on-site scenario cases. While the sum of the energy contents of products (E_P) was higher than that of external energy inputs, except feedstock (E_X), i.e., non-renewable, the value of EROI was greater than 1. From the tendency models of Fig. 5, the transportation distance and treatment capacity were 114.72 km and 251,533 tons/year, respectively, when the EROI value was 1. Therefore, distance and capacity higher than 114.72 km and 251,533 tons/year, respectively, for on-site pretreatment were not suitable for the process from ELCA. Considering the NER value, the distance and capacity were 78.34 km and 137,152 tons/year, respectively, when NER was equal to 1 and E_P was two times E_X. While η_E was at 60%, the distance and capacity were 89.69 km and 172,833 tons/year, respectively.

Modern day gasification units are for the most part based on an integrated gasification combined cycle (IGCC) and produce electricity along with hydrogen/methanol/FT liquid fuels/chemicals/synthetic natural gas or any combinations of these. The major units of an IGCC plant are feed preparation and feeding systems, gasification units, gas separation and cleaning units, water gas shift reactors, turbines and heat exchangers. Generally speaking, the maximum η_E for IGCC is about 60% [22]; therefore, the suggested transportation distance and treatment capacity are below 89.69 km and 172,833 tons/year, respectively. When η_E was around 60%, the EROI and NER were near 1.88 and 0.88 (scenario case E), respectively. Therefore, the suggested criteria for better

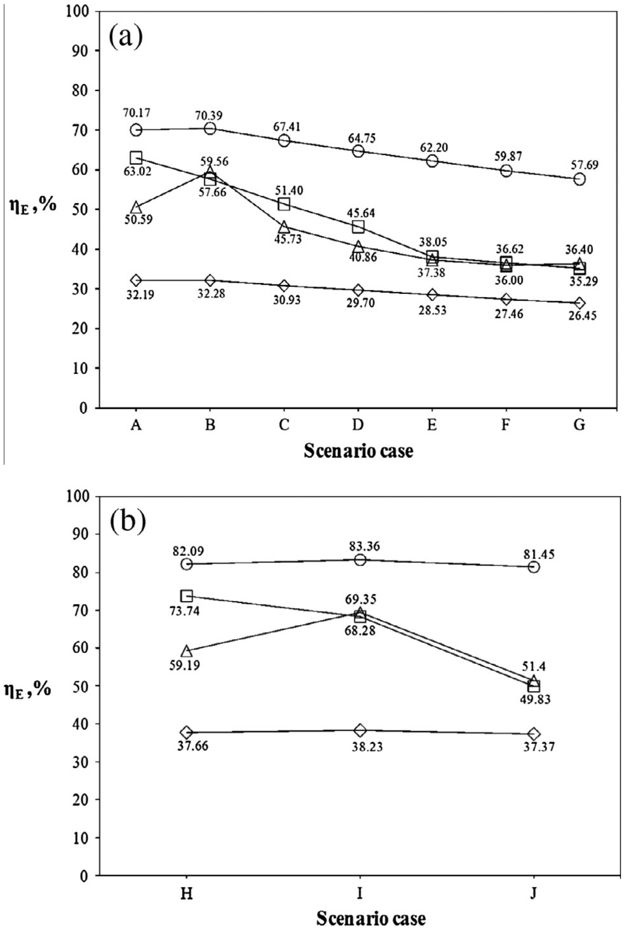

Fig. 4. η_E value of the bioenergy production from rice straw in the ELCA. (a) Off-site and (b) on-site. ○: LCAPTS. □: LCADGS. △: LCARFPS. ◇: LCAMWS.

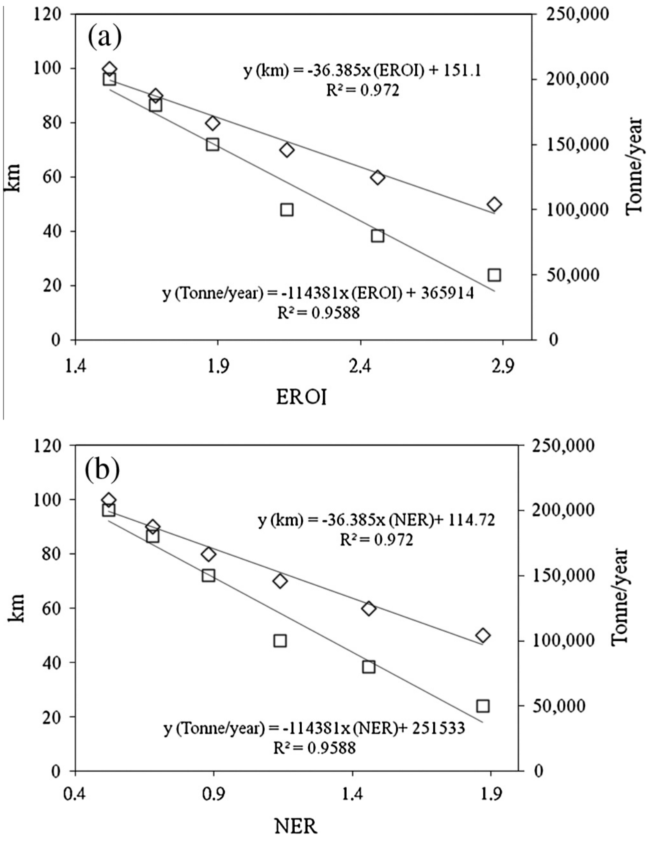

Fig. 5. Tendency simulation models of EROI, NER and η_E values of LCAPTS at on-site scenario cases. (a) ◇: EROI vs. km, □: EROI vs. tonne/year and (b) ◇: NER vs. km, □: NER vs. tonne/year.

appreciation of the developing scenarios used in other evaluation applications would be $\eta_E > 60\%$, EROI > 2 and NER > 1. Such a model is a simple case about LCAPTS and does not consider the interaction of feedstock inputs or combination of gasification techniques, such as co-gasification. Nevertheless, a mathematical model can be based on thermodynamic computations which can predict the trends and values of output information at different feedstock ratios, thus providing useful indications for the optimal choice [23].

4. Conclusion

The energy inputs required in the transportation and pretreatment stages were the greatest components of energy use for on-site pretreatment. Every thermo-treatment technology had positive energy benefits for all on-site scenario cases, as well as at the off-site scenario cases, except when the transportation distance was above 60 km vs. 80,000 tons/year. The results indicated that the transportation of rice straw accounted for the majority of energy consumption for off-site pretreatment. The on-site pretreatment and simulation from the tendency model resulted in a suggested transportation distance and treatment capacity below 114.72 km and 251,533 tons/year, respectively, and an EROI value greater than 1 for the limitation scenario. Also, a transportation distance and treatment capacity of below 89.69 km and 172,833 tons/year, respectively, were suggested for a maximum η_E higher than 60%. Therefore, briquetting on-site for RDF to reduce the transportation energy is an alternative to the natural drying process using solar energy in the energy recovery of rice straw.

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